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[RUSH] **MESSAGE:** Specification:

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REV 10/04

FIBER AMPLIFIER SYSTEM FOR PRODUCING VISIBLE LIGHT

CROSS-REFERENCE TO A RELATED APPLICATION

This application is a continuation in part of commonly assigned co-pending U.S. Patent Application serial number 09/927,145 to Thomas Kane and Mark Arbore, entitled "COMPOUND LIGHT SOURCE EMPLOYING PASSIVE Q-SWITCHING AND NONLINEAR FREQUENCY CONVERSION, filed August 10, 2001," the disclosures of which are incorporated herein by reference. This application is also related to commonly-assigned US Patent Application Serial No. 10662086 ~~(Agent's Docket Number LEL-010)~~ to Thomas J. Kane entitled "HIGH REPETITION RATE PASSIVELY Q-SWITCHED LASER FOR BLUE LASER BASED ON INTERACTIONS IN FIBER," which is filed concurrently herewith and the disclosures of which are incorporated herein by reference.

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GOVERNMENT RIGHTS IN THE INVENTION

This invention was made under contract # F29601-01-C-0246 of the United States Air Force. The government has certain rights in this invention.

FIELD OF THE INVENTION

The present invention relates generally to compound light sources employing lasers with passive Q-switches and nonlinear frequency converters to generate light in a desired wavelength range.

BACKGROUND OF THE INVENTION

Many applications require reliable, stable and efficient spectrally-pure high-power light sources. For example, image projection systems require light sources which exhibit these characteristics and deliver in excess of 1 Watt average power. These light sources should be inexpensive to produce and they need to generate output frequencies in the blue range and in the green range. For other applications light in the UV range is required.

The prior art teaches various types of light sources for generating light in the visible and UV ranges, including frequencies corresponding to blue and green light. A number of these sources rely on a nonlinear frequency conversion operation such as second harmonic generation (SHG) to transform a frequency outside the visible range, e.g., in the IR range, to the desired visible or UV frequency. For example, U.S. Pat. No. 5,751,751 to Hargis et al. teaches the use of SHG to produce deep blue light. Specifically, Hargis et al. use a micro-

amplified by the fiber. The amplified light then leaves the fiber and enters a nonlinear frequency-converting element, preferably comprising one or more nonlinear crystals such as lithium borate (LBO). The resulting frequency-converted light is the desired, generally visible light. Embodiments of the present invention are free of stimulated Brillouin scattering (SBS) and have levels of self-phase modulation that does not reduce frequency conversion to the visible.

I. Fiber Amplifier System

FIG. 1 illustrates a fiber amplifier system 10 according to an embodiment of the invention. The fiber amplifier system 10 has a passively Q-switched laser (PQSL) 12, a fiber amplifier 14 and a nonlinear frequency converting element 60. The PQSL 12 generates a primary beam 34 of primary pulses 36. The primary pulses have a pulse length less than about 1.7 nsec and sufficiently large to facilitate frequency conversion in the nonlinear element 60, e.g., greater than about 100 psec. The PQSL 12 preferably produces the pulses at a sufficiently large repetition rate, e.g., greater than about 100 kHz. The fiber amplifier system 10 can also have a PQSL pump source 16 for producing PQSL pump light 20 that pumps the PQSL 12. In this embodiment, the PQSL pump source 16 is a laser equipped with a wavelength tuning mechanism 18. Such a laser can be designed to deliver PQSL pump light 20 in the form of a continuous wave (cw) light beam. Many types of lasers are suitable for use as the PQSL pump source 16. For example, diode lasers emitting PQSL pump light 20 within the 750 nm to 1100 nm range can be used. The power level of these diode lasers can be between 100 mW and 4000 mW.

A lens 22 is provided before PQSL pump source 16 for focusing pump light 20 and directing it to an input coupler 24 of Q-switched laser 12. Input coupler 24 is designed to admit pump light 20 into a cavity 26 of passively Q-switched laser 12. Cavity 26 has an optical path length L defined between input coupler 24 and an output coupler 28. Although in the present embodiment cavity 26 is linear and couplers 24, 28 are in the form of mirrors, a person skilled in the art will appreciate that other types of cavities and coupling elements can be used, see e.g., commonly-assigned US Patent Application 10662086 ~~(Agents Docket Number LEL-010)~~, which has been incorporated herein by reference.

Cavity 26 contains a gain medium 30. Gain medium 30 exhibits a high amount of gain per unit length when pumped with PQSL pump light 20. Typically, high gain is achieved by providing a high doping level in gain medium 30 within the cross section traversed by light

During operation, pump source 16 is tuned by mechanism 18 to generate pump light 20 in the form of a cw beam at the requisite wavelength to pump gain medium 30. Passively Q-switched laser 12 is adjusted such that primary pulses 36 of primary beam 34 are controlled. To achieve this, one notes that a round-trip time, t_{rt}, of cavity 26 is related to the optical path length L of cavity 26 by the equation:

$$t_{rt} = \frac{2L}{c}$$

where c is the speed of light. Hence, round-trip time t_{rt} can be set by selecting optical path length L of cavity 26. The optical path length L takes into account the indices of refraction of the components that make up the cavity.

Meanwhile, passive Q-switch 32, (e.g., a saturable absorber Q-switch) is adjusted by setting its inter-pulse time. This is done by choosing the appropriate saturable loss, q_o, of the absorbing material and using the fact that the repetition rate of passive Q-switch 32 is proportional to pump power or the power level of pump light 20, and that increasing the repetition rate produces longer primary pulses 36. These parameters can be adjusted to obtain the appropriate inter-pulse time; for more information see, e.g., G. J. Spuhler et al., "Experimentally Confirmed Design Guidelines for Passively Q-Switched Microchip Lasers Using Semiconductor Saturable Absorbers", J. Opt. Soc. Am. B, Vol. 16, No. 3, Mar. 1999, pp. 376-388 (hereinafter Spuhler), which is incorporated herein by reference. Although Spuhler provides adequate guidelines for PQSL systems providing 1064-nm output, PQSL systems that produce 914-nm radiation, e.g., those using Nd:YVO_4 as the gain medium 30, present much greater problems. Solutions to these problems are addressed in commonly-assigned, co-pending US patent application 10662086 ~~(Agents Docket Number LEL-010~~, which has been incorporated herein by reference.

In a preferred embodiment, optical path length L is very short, e.g., L is on the order of 10 millimeters or less. Preferably, L is even less than 1 millimeter. The inter-pulse time of passive Q-switch 32 is selected such that primary pulses 36 have a pulse duration t_p of about 100 times round-trip time t_{rt} as illustrated in FIG. 2. In addition, passive Q-switch 32 is also set such that the time between successive primary pulses 36 at times t_i and t_{i+1} defining an interpulse separation is at least 100 times pulse time t_p and preferably up to 10,000 times

generally provide pulses less than 50 ps long. In addition, mode-locked lasers tend to be much larger than Q-switched lasers. For example, the largest dimension on a typical mode-locked laser is typically on the order of one to two feet. The largest dimension on a PQSL, by contrast, is on the order of one to two inches.

In order to make a PQSL with the desired pulse length, the length L of the resonator cavity 26 is a critical parameter. There are two reasons to make the resonator cavity 26 very short. First, the pulses get shorter as the resonant cavity gets shorter. Second, the PQSL will oscillate at a single frequency only if the resonator is so short that it supports only one mode of oscillation. The length of the resonator cavity such as that shown in FIG. 3A is almost totally determined by the thickness of the gain medium 84. However, if the gain medium becomes too thin, it won't absorb enough of the PQSL pump light 20 to provide a useful intensity in the pulsed primary beam 34. Usually it is desired to absorb as much radiation as possible. However, the inventors have determined that the PQSL 12 can operate effectively with the desired pulse length even if the gain medium is so thin that it absorbs less than half of the PQSL pump radiation. For 1064 nm, design of the PQSL to obtain the desired pulse length is relatively straightforward. Spuhler, e.g., indicates that the pulse period (pulse length) T_{pulse} for a PQSL can be determined from

$$T_{pulse} = \frac{3.52 t_{rt}}{q_0}$$

where t_{rt} is the round trip pulse time defined above and q_0 is the saturable loss in the passive Q-switch in the PQSL. For radiation corresponding to certain transitions, e.g., the 914-nm transition in Nd, additional design considerations must be taken into account. A PQSL for producing 914-nm is described in US Patent Application serial number 10662086, ~~(Agents Docket Number LEL-010)~~, which has been incorporated herein by reference.

IV. Fiber Design

In addition to the pulse format, optimized frequency conversion requires optimization of the fiber amplifier 14. The following discussion addresses issues of fiber design.

A. Figure of Merit

The inventors have found that, due to the limitations imposed by Raman scattering, a fiber's capacity to generate light depends on the product of its absorption β of pump light 40 (measured in dB/m), and the mode area of the light to be amplified, A_{mode} measured in square